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USING BACKSCATTERED LIGHT

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OPTICAL DIAGNOSTICS OF CO_2 LASER-FUSION TARGETS USING BACKSCATTERED LIGHT*

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Abstract

With the f/2.4 focusing optics on one of the eight Helios CO_2 laser beam lines, direct backscattered light from a variety of glass microballoon targets has been observed. The quantities that have been measured include: (1) the total backscattered energy; (2) relative amplitudes of the backscattered fundamental and low harmonics ($n=1$, 2, 3) of the 10.6 μm incident light; (3) the 3/2 harmonic emission from a double pulse backscatter experiment; (4) the temporally resolved 10.6 μm light using a fast pyroelectric detector and a Los Alamos 5-GHz oscilloscope; and (5) the time-integrated spectrally resolved fundamental using a 3/4 meter spectrometer and a high resolution pyroelectric detector array (resolution ~ 40 Å at 10.6 μm). The suitability of these diagnostics for evaluating the CO_2 laser plasma in terms of stimulated scattering processes, plasma density gradients, velocity of the critical surface, etc., is discussed.

Introduction

Although most of the primary diagnostics of laser-driven pellets in the inertial confinement fusion (ICF) program are close-in diagnostics, being on the order of 0.1-1 m distant from the targets and observing such quantities as x-rays, fast ions and neutrons, there is a class of useful diagnostics which can be utilized quite distant from the targets. These optical diagnostics sample target scattered laser light which contains useful information about the laser-matter interaction in the pellet. Depending upon optical layout of the system, the scattered light can be routed away from the target interaction area and hence away from the severe EMI and x-ray environment associated with these high-power short-pulse lasers. This scattered light can be spectrally, temporally, and spatially resolved to provide some understanding of the absorption process at the target plasma "critical" surface. This is the surface where the density of electrons is such that the local plasma frequency $\omega_p = (4\pi n e^2/m)^{\frac{1}{2}}$ is equal to the laser frequency ω_0. For CO_2 laser light at 10.6 µm, this critical density is $n_c \simeq 10^{19}$ cm^{-3} and an important part of the ICF program is an understanding of how laser light is absorbed at this surface.

Backscatter Diagnostic Facilities

In Helios, the 10 kJ eight-beam CO_2 fusion laser system in Los Alamos, the beam paths are situated such that it is relatively easy to accept a sample of the direct backscattered light from the f/2.4 focusing optics inside the target chamber. As illustrated in Fig. 1 the 16-inch-diameter NaCl output windows on the CO_2 power amplifiers are tilted at 10^0 to the beam paths. Since these

windows are anti-reflection coated for 10.6 μm on one side only, the
uncoated side provides a 4% Fresnel reflected sample of the
retropulse, which is headed directly back into the amplifier.
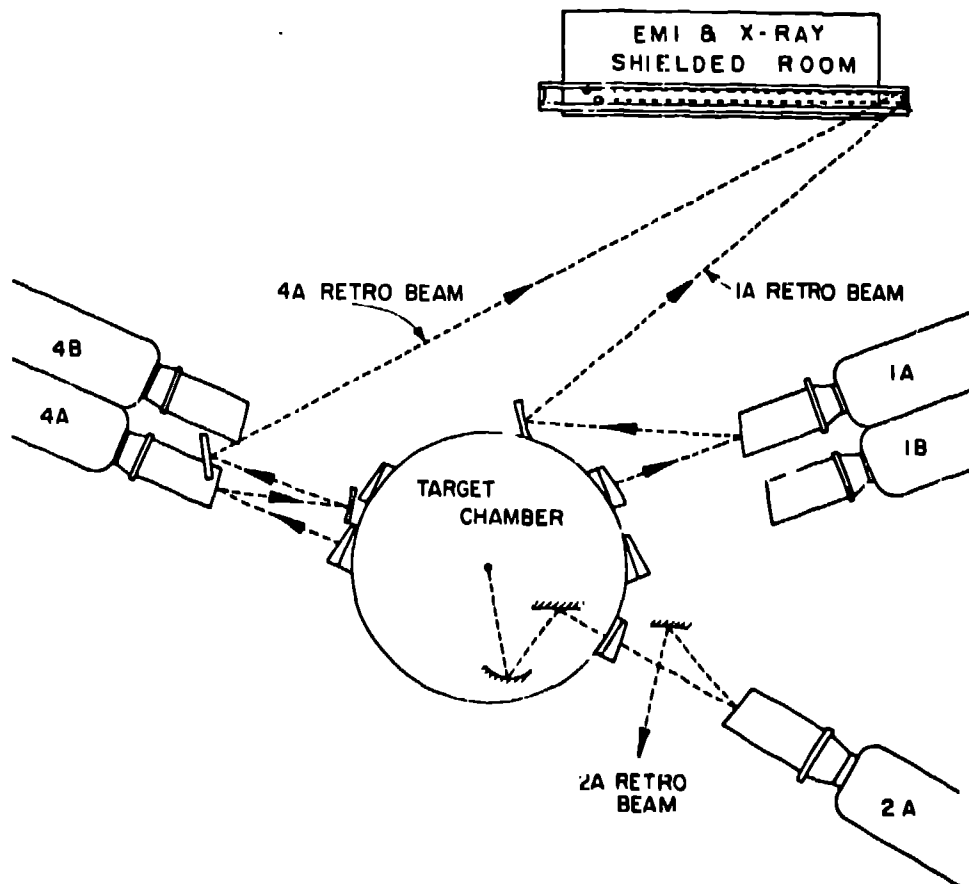
Figure 1.   Optical beam paths in Helios showing three
             retro-channels; the 1A/4A backscattered beams focus down
             and pass through waveguide shields in the diagnostic
             screen room. The 2A backscattered beam from the f/2.4
             off-axis paraboloid inside the target chamber (shown) is
             relayed to the forward-going diagnostic screen room.
             Amplifiers 2B, 3A, and 3B have been omitted for clarity.

Figure 1 shows that there are a total of three beamlines for which there are 16-inch-diameter focusing mirrors on the retrobeams. Lines 1A an   are new optical trains which focus backscattered light into a double electrically isolated and lead-lined screen room that will be devoted to backscatter diagnostics. The 2A retrochannel has been operational for a year and shares the screen room facility with the eight forward-going beam diagnostics samples; all the data presented in this paper were obtained from the 2A retro-channel.

Energy Measurements

In all cases the energy measurements in the 2A retrochannel utilized pyroelectric joulemeters whose outputs were recorded on storage oscilloscopes. Harmonic energy measurements were made with bandpass interference filters in front of the joulemeters; the ratio of harmonic energy content to total backscattered energy was obtained by placing a NaCl splitter before the harmonic filter and measuring the total spectrum. With the exception of the "double-pulse" experiment, all shots refer to a nominal 1-ns pulse width with up to 1 kJ of energy in the forward-going 2A beamline. The backscattered energy measurements are summarized in Table I which is a compilation of > 100 total shots.

TABLE 1

Target Type	Irradiation	$\dfrac{E_{back}}{E_{forward}}$	$\left(\dfrac{2\omega_0}{\omega_0}\right)_{back}$	$\left(\dfrac{3\omega_0}{\omega_0}\right)_{back}$	$\left(\dfrac{3/2\omega_0}{\omega_0}\right)_{back}$
Glass Microballoon uncoated; CH, Au or W coated	~5×10^{15}W/cm^2 Normal Incidence	$\dfrac{51J}{800J}$ (6.4%)	$\dfrac{0.73J}{51J}$ (1.4%)	$\dfrac{0.15J}{51J}$ (0.3%)	-0-
Au Shell	~5×10^{15}W/cm^2 53^0 off normal	$\dfrac{14.4J}{928J}$ (1.6%)	$\dfrac{0.14J}{14.4J}$ (1.0%)	——	——
Solid Glass	~5×10^{15}W/cm^2 Double Pulse	$\dfrac{46J}{1028J}$ (4.5%)	——	——	$\dfrac{~4mJ}{46J}$ (0.01%)

Backscattered energies from the Helios 2A retro-channel. All tabulated energies are those which would be measured at the target based on Fresnel-reflected samples of both the incident and reflected light. Harmonic energies are expressed as a fraction of the total backscattered energy.

The following conclusions can be drawn from these tabulated
energies:

1. The direct backscattered energy at these high intensities
    ($>10^{15}$W/cm^2) is always a small fraction ($<10\%$) of the
    incident energy. Although there is a lot of fluctuation in
    the data the average reflected energy is about 6% of the
    incident 2A energy.

2. The total direct backscattered energy from the 1-ns laser
    pulse at normal incidence on a glass microballoon (GMB)
    target is relatively independent of the coating material on
    the GMB. The data shown include shots on bare GMBs, and
    GM_s with CH, Cu, Au, and W coatings.

3. Most of the direct backscatter is specular; the reflected
    energy drops by a factor of 3 to 4 when the target normal
    is rol.ted away from the incident laser light. This was
    observed both with 2-mm-diameter gold shells, for which the
    laser light was incident at 53° to the normal and for
    flat Cu targets for which the laser light was 55° to the
    target normal.

4. Roughly 20% of the observed backscattered energy is due to
    scattering and/or refraction through the target plasma of
    energy from beamlines other than 2A. This observation is
    based on ~ 6 shots for which the entire system except for
    2A was fired, and the 2A retrochannel recorded energy at
    approximately 20% of the value which would have been
    recorded had the 2A beamline been operating.

5.   The low harmonics of the 10.6 μm laser light are created
     quite copiously in the target plasma, with the second
     harmonic alone accounting for more than 1% of the total
     backscatter. This is a somewhat higher yield than has been
     observed on flat targets at lower intensity (10^{14}
     W/cm^2) [1]. However, the ratio of third to second
     harmonic production, 1/5, is approximately the same as in
     Ref. [1].

     Since the harmonics are generated near the surface where
     the incident laser light is absorbed, i.e., the critical
     surface, then any spectral, temporal, or spatial
     information obtained relates directly to the critical
     surface. The second harmonic spectrum, for example, may
     provide a convenient decoupling of the backscattered 10.6
     μm spectral shifts due to stimulated Brillouin scattering
     and Doppler shifts from the motion of the critical surface,
     since the second harmonic should not be affected by
     Brillouin scattering.

6.   The $3/2\omega_0$ harmonic has never been observed within the
     limits of sensitivity of the pyroelectric joulemeters, from
     single pulse irradiation of GMB targets at Helios. It was
     observed, however, on all five shots of a double-pulse
     experiment in which two 1-ns pulses separated by 11 ns were
     injected into the 2A beamline and irradiated a solid glass
     300 μm diameter spherical target. This result should not
     be surprising, since the presence of the $3/2\omega_0$ harmonic

is indicative of a shallow density profile in the target plasma. The $3/2\omega_0$ harmonic is generated by the 2-plasmon decay instability at quarter-critical density. This instability is enhanced when there is a relatively large amount of underdense plasma near quarter critical density. This is the case when the first 1-ns pulse creates a plasma on the surface of the target, and the plasma expands freely for 11 ns. It is the interaction of the second 1-ns pulse with the underdense plasma from the first pulse which produces $3/2\omega_0$. This is a potentially useful diagnostic tool in that any temporally, spectrally or spatially resolved $3/2\ \omega_0$ relates directly to the quarter-critical surface.

Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) is a plasma instability in which an incoming photon at frequency ω_0 decays into an ion acoustic wave at frequency ω_i and a backscattered photon at ω_s following the relationship

$$\omega_0 \rightarrow \omega_s + \omega_i$$

such that $\omega_i \ll \omega_s$. The signature for this process is a slightly reshifted backscatter spectrum where the amount of red shift is related to the plasma temperature at the scattering site[2]. Quantative measurements of SBS red shift, however, must unfold spectral shifts due to the Doppler effect. Recently a great deal of theoretical work on laser light induced SBS has been undertaken [3, 4], since this process represents a loss mechanism in

the coupling of laser light to the target. Experimentally it has been observed that SBS from 10.6 μm laser plasmas saturates at relatively low values [5-8] and this work is no exception. Even in the extreme case of the double-pulse experiment listed in Table 1 where SBS should have been enhanced in the underdense plasma the total backscatter was less than 5% of the incident energy, and of this only a small fraction may be a Brillouin component. Theoretical interpretations of the causes of SBS saturation include ion heating and trapping [3, 4], density profile steepening effects [9], and wave breaking [10], and in general imply a limitation on the amplitude of the ion wave that can build up in the target plasma.

Spectrally Resolved Backscatter

Backscattered spectra from the 2A retrochannel were obtained with a 3/4 m Jarrell-Ash spectrometer inside the diagnostic screen room. The detector placed at the exit focal plane of the spectrometer is a 32-element high resolution pyroelectric array* with elements on a 100 μm center to center spacing. A 50 line/mm grating produces sufficient dispersion such that successive rotational lines in the CO_2 10.6 μm P-branch [e.g. P(18) and P(20)] are separated by nine elements in the array. The overall resolution as determined by the entrance slit width and diffraction-limited spot size from the final mirror in the spectrometer is approximately 40 Å at 10.6 μm, or one-fifth the 200 Å separation between P(18) and P(20). With this resolution the sensitivity to motion of the critical surface via Doppler shifted backscatter is approximately 5×10^6 cm/sec. The shift in

*Manufactured by Spiricon, Inc.

wavelength $\Delta\lambda$ of light that is reflected from a moving critical surface is given by

$$\frac{\Delta\lambda}{\lambda} = 2\frac{v_c}{c} \qquad (1)$$

where λ is the wavelength of the incident light, c is the velocity of light, and v_c the velocity of the critical surface.

The response of the spectrometer to a multiline oscillator pulse from the Helios front end is shown in the lower trace of Fig. 2. This calibration was obtained by retroreflecting the weak front end pulse from an alignment sphere at the center of the target chamber. The upper trace in Fig. 2 is an actual backscattered spectrum from a 1-ns pulse on a spherical Cu target. Clearly the backscattered spectrum is substantially broadened, to the extent that there is overlap from adjacent rotational lines. Since the relative amplitudes of these lines is not routinely monitored at the output of the power amplifiers, interpretations of a red or blue shifted peak will be simplified when the oscillator is operated on a single rotational line.

With a response time of approximately 1 ms, the detector array produces a time-integrated spectrum of the 1-ns pulse. If there is both a Doppler red shift (critical surface moving radially inward) and a blue shift (critical surface moving radially outward) at different times during the pulse, the resulting spectrum is simply broadened and the usefulness of the spectrum remains in determining an approximate upper limit to the velocity of the critical surface.

RED   ↑   BLUE
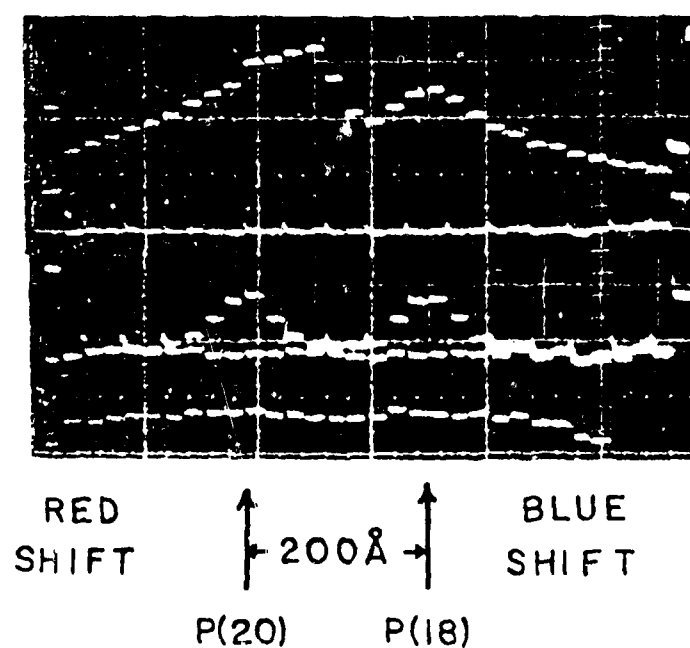SHIFT   ⊢ 200Å ⊣   SHIFT

P(20)   P(18)

Figure 2.   (a) The backscattered 10.6 μm spectrum from a Cu target
using the 3/4 m spectrometer and high-resolution
pyroelectric array detector. (b) The calibration trace
showing the P(18) and P(20) lines from the Helios
multiline front end oscillator.

This limit includes any contribution to red shift from stimulated Brillouin scattering. From the spectrum shown and from the few other spectra obtained on similar targets, no peak is shifted by more than 80 Å, and no substantial contribution to a broadened line is coming from more than 200Å from the line center. Equation (1) then yields a conservative upper limit on the critical surface velocity at 3×10^7 cm/sec.

Temporally Resolved Backscatter

Figure 3 shows a temporally resolved 10.6 μm backscatter pulse from a 300-μm-diameter glass target. The detector used for this measurement is a modified Molectron P5-00 fast pyroelectric and a Los Alamos 5 GHz oscilloscope. The calibration trace superimposed on the pulse shape was obtained from a 3.5 GHz signal generator. While the incident pulse (not shown) is smoothly varying in time, the backscattered pulse clearly shows some structure which may be indicative of the growth and decay of instabilities in the plasma. Temporal structure has been observed in other 10.6 μm backscatter experiments [6, 7] although no effort has apparently been made to quantitatively relate observed structure to any theoretical models.

Temporally resolved harmonics of the 10.6 μm laser light should prove to be a useful diagnostic since these are generated at the critical surface. Timing of the fundamental backscatter and of the harmonics relative to the incident pulse, something which has not yet been achieved at Helios should yield time dependent absorption data of great interest in the theoretical simulations of the laser plasma interactions.
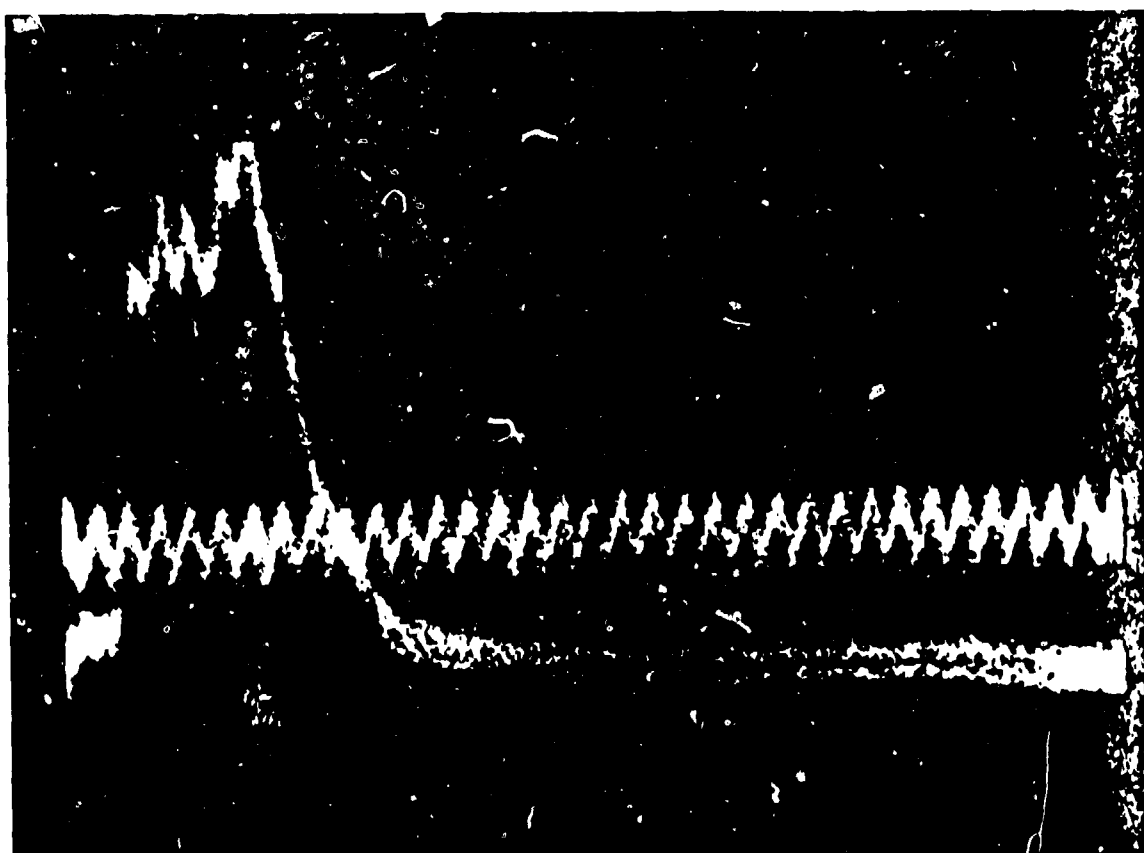
Figure 3.   Temporally resolved backscatter from a solid glass
target using a fast pyroelectric detector and 5 GHz
oscilloscope.

Acknowledgements

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